

# **NOTICE**

**All drawings located at the end of the document.**

**CONCEPTUAL MODEL FOR ACTINIDE MIGRATION STUDIES AT  
THE ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE**

**October, 1998**

**Rocky Flats Environmental Technology Site  
Golden, Colorado 80402**



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## 1.0 INTRODUCTION

### 1.1 Conceptual Models

Conceptual models are developed in an environmental investigation and remediation context to understand the effects of a site's physical and chemical characteristics on the transport of contaminants. Conceptual models are a tool to evaluate and understand the relationships between surface and subsurface geology, soils, hydrology, meteorology, contaminant sources, contaminant types, and contaminant fate and transport (i.e., distribution processes in soil, sediment, air, groundwater, and surface water). The development of a conceptual model for actinide transport at the Rocky Flats Environmental Technology Site (RFETS or Site) is an iterative process whereby the available data are compiled and integrated into an overall understanding of actinide behavior in the environment at the RFETS (Rocky Mountain Remediation Services [RMRS], 1997).

The Site conceptual model will provide both a qualitative understanding of actinide (herein considered as plutonium [Pu], americium [Am], and uranium [U]) sources and transport pathways for the Walnut Creek and Woman Creek watersheds (shown on Figure 1) and associated airsheds and quantify the transport rates for each pathway for Site conditions. The purpose of the conceptual model is to provide a framework for quantitative data to be used to evaluate the following questions, as stated in the Actinide Migration Studies (AMS) Data Quality Objectives (RMRS, 1998a):

- 1 Urgent What are the important actinide migration sources and migration processes that account for recent surface-water quality standard exceedances?
- 2 Near-term What will be the impacts of actinide migration on planned remedial actions? To what level do sources need to be cleaned up to protect surface water from exceeding action levels for actinides?
- 3 Long-term How will actinide migration affect surface water quality after Site closure? In other words, will soil action levels be sufficiently protective of surface water over the long-term?
- 4 Long-term What is the long-term off-site actinide migration, and how will it impact downstream areas (e.g., accumulation)?

The Site Actinide Migration Conceptual Model will be constructed based on investigations at RFETS, studies conducted at other DOE sites and research institutions, and current knowledge of RFETS geology, hydrology, and meteorology. It will incorporate the current level of understanding of relationships between actinide distribution, soil types, hydrogeology and meteorology, and the potential effects of actinides on surface-water and air quality resulting from their transport from source areas. Existing transport models will be incorporated into the conceptual model in order to efficiently estimate the transport rates necessary to answer the previously stated questions (RMRS, 1997).

Data deficiencies and areas of uncertainty will be identified during this process. Therefore, quantification of the conceptual model may require collection of additional data and integration of the new data into the model to fill the data deficiencies or to address specific areas of uncertainty.

The Site Actinide Transport Conceptual Model is a living document that will be revised and formally updated as new data are obtained by the AMS Group. Data that are currently available, or become available from Site-wide and project-specific modeling, monitoring, and characterization will continue to be compiled, reviewed and analyzed to confirm, enhance, or modify the current conceptual model. The model will help evaluate the final RFETS configuration and long-term surface-water quality protection.

## **1.2 Actinide Transport**

The transport of actinides in the environment can include both physical and chemical processes. Since actinides in the environment occur at low concentrations, transport processes are intimately associated with other materials. Physical transport is the movement of the material that contains the actinides. For example, actinides within or adsorbed to the particles that make up soils and sediments can be moved and redistributed by surface water, groundwater, or wind. Such physical particle transport can occur on an individual particle level as dust in the air or suspended solids in water, up through integrated movement such as landslides.

Chemical transport processes of actinides in the environment take place within the context of the physical processes. Chemical reactions may involve a range of processes. At one extreme, the actinide(s) might remain unchanged at the molecular and atomic scale while the associated materials react and change. At the other extreme, the actinide(s) may react while the surrounding materials remain relatively unchanged. For example, radioactive decay of actinide atoms results in formation of different elements, the potential for changes in oxidation/reduction state and the potential for changes in local structural environments. An additional variable is relative behavior among the actinides. Pu and Am have low solubilities in water and so are primarily associated with other particulate materials, while U has a higher solubility and is more susceptible to dissolution and transport in the solution phase (Langmuir, 1997).

Dissolved components are potentially the most mobile, because the constituent can move at the same rate as the water. Particulate phase transport in surface water is intrinsically slower because particles settle out in quiescent areas, requiring resuspension of particles for transport to continue. However, relative distribution and reactions between dissolved and particulate forms controls both the amounts and absolute rates of actinide movement in the environment, and ultimate transport rates. In addition, the size and characteristics of particulate phases are widely variable depending on many factors, which include chemical composition, time and history. Even the definition of dissolved relative to particulate components is at least partly dependent on measurement techniques and the level of detail involved in characterization. Therefore, it is important to characterize the distribution of the transported material in the dissolved and particulate phases, and to understand the environmental conditions, which cause reactions between phases. These transformations can include disintegration or aggregation of sediment particles, aggregation of chemical components to form complexes, polymers or particles, and chemical oxidation-reduction, dissolution, or precipitation of particle components to change surface or bulk properties.

Amorphous and poorly crystalline coatings in soils and sediments are highly reactive sites for chemical reactions. These materials are generally composed of hydrous oxides of iron, aluminum, manganese, and silicon, carbonates, and organic substances. These coatings can act as mortar, cementing together individual particles to form larger secondary

aggregates. These coatings are typically chemically dynamic and might respond more quickly than the remainder of the soil or sediment components to changing environmental conditions. When involved in interactions with actinide(s), such reactions may be directly susceptible to dissolution under variable and extreme environmental conditions, thus temporarily liberating associated actinide(s) into the solution for transport or chemical reaction (RMRS, 1995, Litaor et al, 1996a, 1996b, and 1998)

The result of these numerous factors involved in actinide transport, including physical, chemical and site specific history, is distinct variability in detailed transport processes between different sites. Therefore, basic understanding of actinide chemical structure and thermodynamics must be combined with site-specific chemical and physical transport characterization, so that the present and future state(s) of actinides within the environment can be incorporated into remedial options and design. Attachment A identifies the data needs for modeling the dominant actinide transport processes that are believed to control actinide transport from contaminated Site soils.

Figure 2 illustrates the environmental media that may be contaminated with actinides and potential transport pathways, where "R" denotes the various rates of transport and the subscripts designate the transfer-specific processes.

Actinides are redistributed among media via the migration pathways. Transport processes contain both horizontal and vertical components.

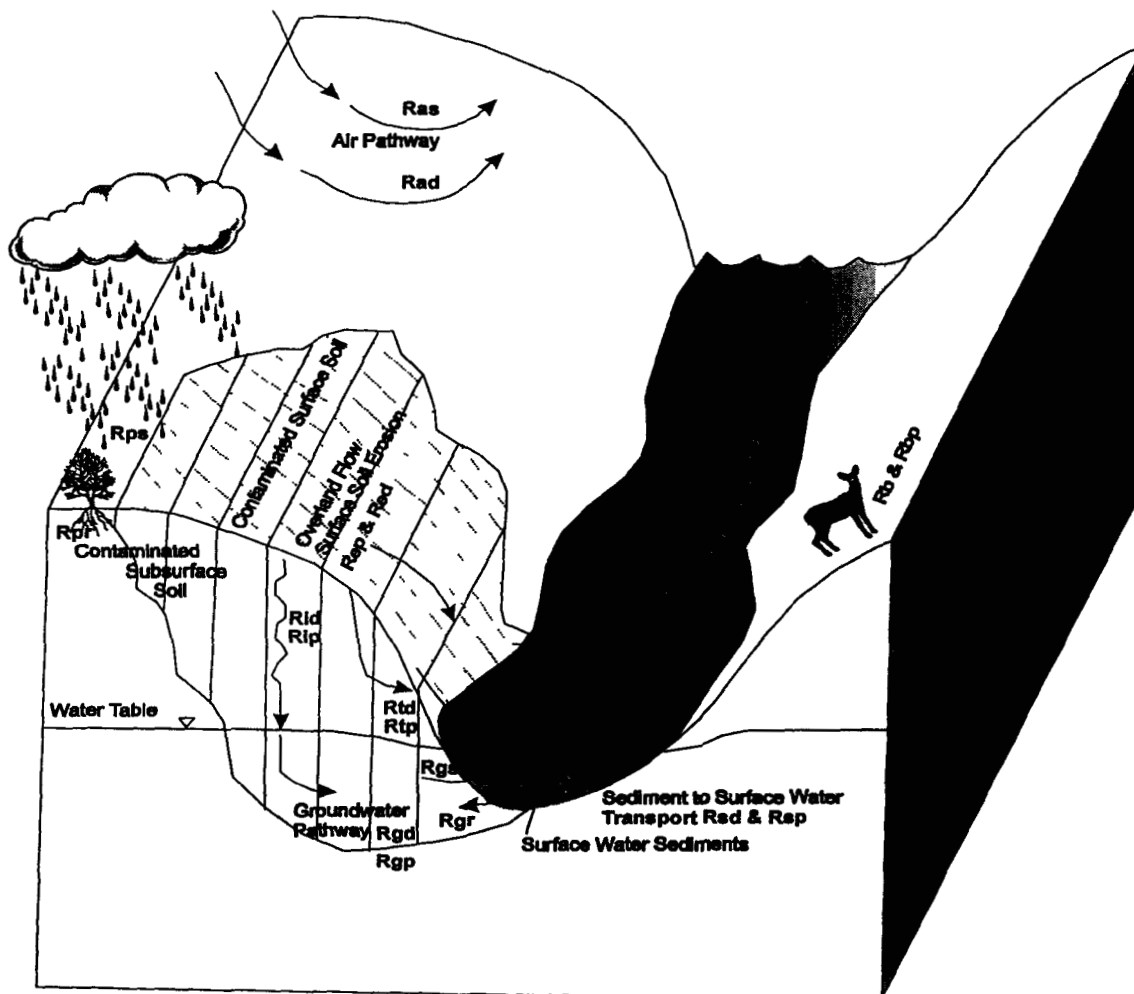
## **2.0 ACTINIDE SOURCES AT ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE**

Actinide transport is being evaluated along surface water and groundwater pathways at RFETS. Areas of primary importance that have actinide contamination include the Industrial Area (IA), the South Walnut Creek watershed, the North Walnut Creek watershed, and the Woman Creek watershed (Figure 1). The Walnut Creek watershed receives most of the IA drainage and includes the South Walnut Creek and North Walnut Creek watersheds, No Name Gulch (aka), the Landfill Pond drainage, and portions of the McKay Ditch drainage. The southern portion of the IA drains into the South Interceptor Ditch (SID)/Woman Creek watershed.

The Walnut Creek and Woman Creek (including the SID) watersheds are being evaluated by the AMS. Woman Creek and Walnut Creek can be subdivided into sub-basins in order to study transport processes on a manageable scale. Actinide transport in the Rock Creek watershed will not be studied due to its spatial and hydrologic isolation from the contaminated portion of the Site. Sources for actinide transport within the Woman Creek and Walnut Creek watersheds are

- Individual Hazardous Substance Sites (IHSSs) in the Buffer Zone,
- Diffuse low-level surface soil contamination,
- Decontamination and decommissioning (D&D) activities in the IA,
- Air emissions, and
- Potentially-unknown IA sources of radionuclide contamination

**Figure 2 – Potential Actinide Transport Pathways at the Rocky Flats Site.**



- R = rate of actinide transport in medium (subscripts indicate transport mechanism)
- Ras = air suspension
- Rad = air deposition
- Rb = bio-uptake
- Rbp = biotransport (including bioturbation and biopedal transport)
- Rep = soil erosion and overland flow particulate/colloid transport
- Red = soil erosion and overland flow dissolved transport
- Rid = infiltration dissolved transport
- Rip = infiltration particulate/colloid transport
- Rgd = groundwater dissolved transport
- Rgp = groundwater particulate/colloid transport
- Rgs = groundwater discharge
- Rgr = groundwater recharge
- Rpr = vegetation root uptake
- Rps = raindrop splash
- Rsp = surface water particulate/colloid transport
- Rsd = sediment to surface water dissolved transport
- Rtp = particulate vadose zone transport (subsurface storm flow)
- Rtd = dissolved vadose zone transport (subsurface storm flow)

Sources of actinide contamination are discussed below and will be incorporated into the Site Actinide Transport Conceptual Model

## **2.1 Individual Hazardous Substance Sites in the Buffer Zone**

Known sources of actinide contamination exist in some IHSSs in the Buffer Zone, including the 903 Pad and Lip Area, the East Trenches area, the Ash Pits, and the Original Landfill. These sites were contaminated by historical waste treatment and disposal practices (Department of Energy [DOE], 1980). These potential source terms are one of the focuses of the AMS investigations, as the clean-up levels for the IHSSs may be influenced by AMS results.

## **2.2 Diffuse Low-Level Surface Soil Contamination**

Low-level contamination of surface soils by Pu and Am occurs throughout the eastern portion of the Buffer Zone (Litaor et al, 1996a and RMRS, 1997 and 1998c). The physical and chemical processes of actinide movement of soils on hillslopes and in ephemeral tributary channels to Woman Creek and Walnut Creek is being investigated using watershed sampling techniques and is a focus of the watershed erosion modeling effort of the AMS.

## **2.3 Decontamination and Decommissioning Activities**

D&D activities present the potential for release of building-related contaminants to the environment. During demolition, actinides in concrete foundations, roof materials, or other building materials could be released to the environment. Therefore, D&D activities are closely monitored to measure and quantify any potential impact on the environment. Monitoring of D&D areas commences in advance of the D&D activity to establish a baseline and will continue well after the D&D activity. The monitoring provides detection and early warning of releases to the environment, as well as a potential means for calibrating actinide transport models (DOE, 1994).

## **2.4 Air Emissions**

Currently, stack effluent emissions are limited to re-emission from deposits in the ducts and minor emissions from current activities. A possible, though unlikely, source of emissions is an accident leading to a breach in the ducts. The quantity of effluent stack emissions to the atmosphere could change as the Site's mission of special nuclear material stabilization, consolidation, and storage, waste management, and environmental restoration is carried out. Effluent stack emissions will decrease as buildings are subjected to D&D. Nevertheless, effluent stack emissions have been and continue to be a potential source of actinide, primarily Pu and Am, introduction to the environment. Other sources of air emissions include D&D and other remediation activities, as well as the resuspension of particulates from surface soils. The monitoring of air emissions is an on-going RFETS program activity, contributing data to the air transport modeling effort of the AMS (EG&G, 1993b).

## **2.5 Potential Undiscovered Industrial Area Sources**

Investigation of the IA environment has identified many major sources of actinide contamination. Additional IA characterization is planned for fiscal year 1999 (FY99) and fiscal year 2000 (FY2K). Unknown sources may be discovered as D&D or characterization

activities are implemented. For example, the removal of buildings or pavement could present new source terms for actinide transport (DOE, 1994)

### **3.0 SITE ACTINIDE TRANSPORT CONCEPTUAL MODEL**

Table 1 summarizes the individual actinide transport processes and potential sources within each drainage basin and identifies the processes that are expected to account for observed actinide movement at the Site. Underlined items in Table 1 identify the specific processes that are believed to be of primary importance within each of the drainage areas. Watershed-based analysis of actinide transport at the Site allows

- Straightforward delineation of geographic boundaries for analysis, and
- Analysis of interaction between surface water and groundwater transport processes

The transport processes shown in Table 1 define the basis for the Site Actinide Transport Conceptual Model.

Schematic diagrams for the Site Actinide Migration Conceptual Model for Pu, Am, and U are shown in Figures 3 and 4. Figure 3 shows that the dominant transport pathway for Pu and Am is through erosion of surface soil and particulate or colloidal transport to surface water. Figure 4 shows that the dominant transport pathway for U is through infiltration, and transport in alluvial groundwater to surface water. All of these transport pathways are discussed below in detail.

Surface water is the most important transport medium at RFETS, determining compliance with the Rocky Flats Cleanup Agreement (RFCA) (DOE, 1996b) and appropriate remediation performance criteria. Past studies of groundwater at the Site (EG&G, 1995a, b, and c) indicate that the most likely route for contaminated groundwater to move off-site is through seepage to surface water prior to leaving the Site.

#### **3.1 Surface Water Transport Pathway**

The goal of the AMS is to understand actinide transport processes to facilitate the long-term protection of downstream surface-water quality, overall environmental quality, and human health by guiding cleanup activities. There are three processes that can primarily lead to actinide transport in surface water: erosion/overland flow, channel flow, and dissolution from pond sediments. These include both physical and chemical transport mechanisms.

##### **3.1.1 Erosion/Overland Flow (Red and Rep)**

Actinides released to the environment typically partition to a solid form that becomes incorporated into surface soils. Contaminated soil may be thought of as any Site soil with an actinide content higher than that found in soils unaffected by Site activities (a  $k_a$  background). These soils are subject to erosion processes that have the potential for transporting actinide-contaminated soil to the Site surface water, leading to exceedances of the surface water standards and potential transport off-site.

Table 1. -- Potential Actinide Transport Processes in Rocky Flats Watersheds.

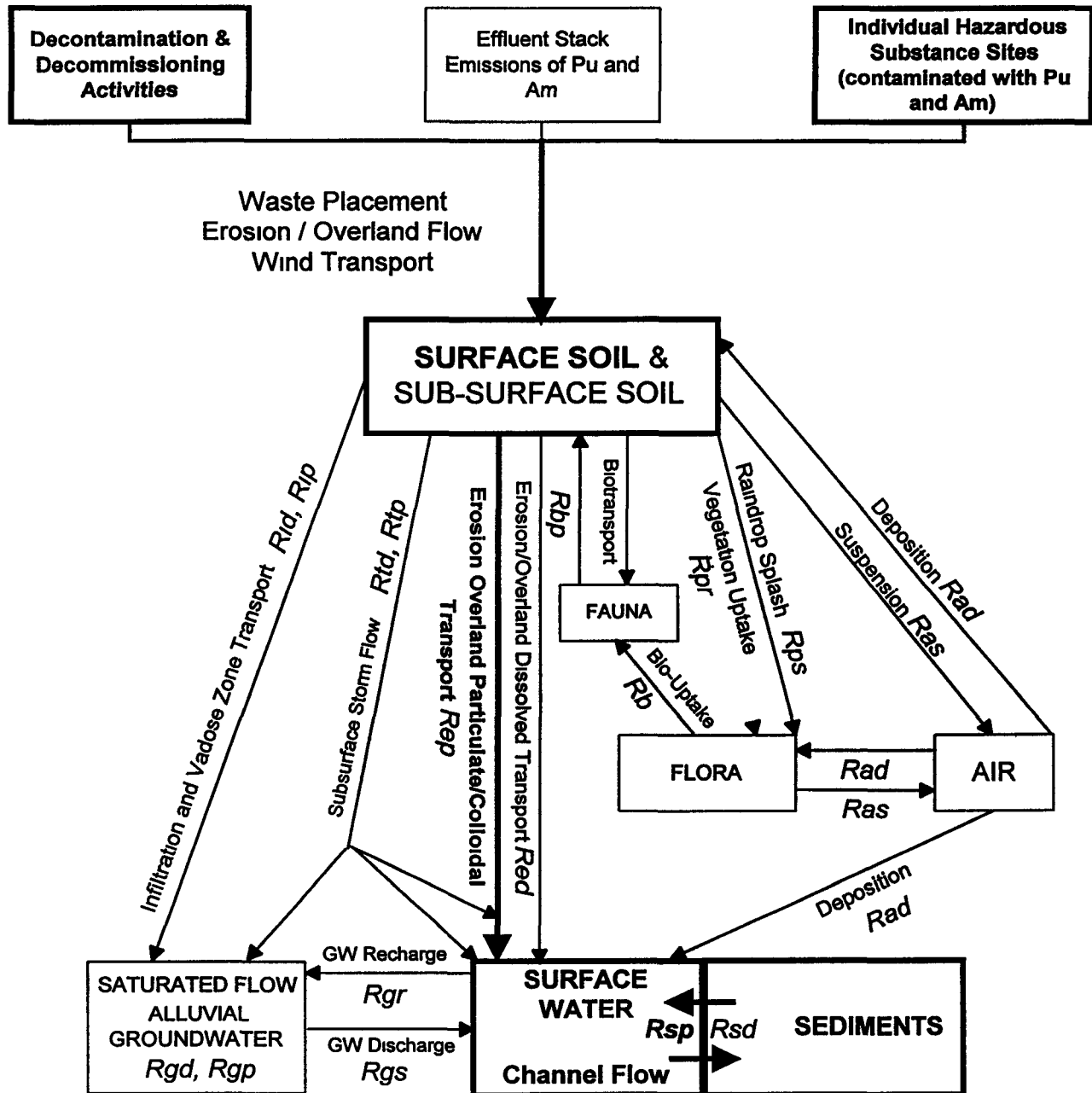
I. Surface Water	
Overland Flow/Erosion (Red and Rep) Particulates Colloids Dissolved	<p>Potential long-term process due to Pu and Am surface soil and exposed sediment contamination Under investigation</p> <p>Smallest particles move the furthest in erosion process Under investigation</p> <p>Low potential for transport for Pu and Am May be more significant for U Investigation underway</p>
Channel Flow (Rsp) Particulates Colloidal Dissolved	<p>Samples collected during storm events indicate that suspended solids from surface soils and resuspension are a significant source of actinides in surface water Under investigation</p> <p>May be significant, under investigation</p> <p>Probably not significant for Pu or Am, may be significant for U Under investigation</p>
Dissolution from Sediments (Rsd)	<p>May be significant for Pu or Am, under certain redox conditions, potentially significant for U</p> <p>Under investigation</p> <p>No Ponds in the IA</p>
II. Groundwater- Unsaturated Flow	
Infiltration (Rid) Dissolution Pu/Am	<p>Transport of dissolved Pu or Am in soils does not appear to be a significant route Detections in groundwater appear to be an artifact from drilling This will be investigated in FY99</p>
Infiltration (Rid) Dissolution U	<p>Dissolution of subsurface U, contamination in the Original Landfill/Asphalt Area may contribute to U groundwater loading</p> <p>U that leached beneath the Solar Ponds and naturally occurring U may be sources of U detected in groundwater in the IA and near N Walnut Creek Naturally occurring U may also be a source</p> <p>Both may serve as continuing sources to surface water</p>
II. Groundwater Unsaturated Flow (Cont.)	
Colloidal (Rip)	<p>Transport of colloids in groundwater has been demonstrated at other sites Macro-pore flow dominates Significance may be</p>

Particulates (Rp)	<p>bounded because it is only for short distances  <u>The movement of particulates and associated Pu and Am down soil macro-channels (e.g. root and worm channels) with infiltrating water has been demonstrated in the 903 Pad/Lip Area (to a depth of 15-20 cm) and probably occurs in soils across the Site</u></p>	
III. Groundwater-Saturated Flow		
Subsurface Storm Flow (Dissolved, Colloidal, and Particulate) (Rgd and Rgp)	<p><u>May be significant over short distances for Pu and Am under extraordinary conditions in the 903 Pad/Lip Area. Significance is not quantified. Significance under investigation.</u></p>	
Groundwater Discharge/Recharge to/from Surface Water (Rgs and Rgr) Dissolved Colloidal Particulate	<p>Probably not significant for Pu or Am, under investigation. A potential process for U in soils at the Original Landfill and the Ash Pits ICP/MS analyses at the Solar Ponds indicates that the U in the Walnut Creek drainage is natural and the U in the vicinity of the Solar Ponds is either depleted or enriched (both depleted and enriched U disposed of at the Solar Ponds).  <u>Significance under investigation.</u>          Probably not significant.</p>	
IV. Air (Rad and Ras) Effluent Systems	<p>Primary operations ceased in 1989. The current activities should continue to be controlled to mitigate additional impacts. Based on air monitoring results, considered negligible to insignificant source for Pu and Am. This will be investigated in FY99.</p>	
Soil Particulates Surface Disturbance	<p>Late-1960s/early-1970s uncontrolled emissions during inventory removal and source mitigation at 903 Pad storage area. Control potential future emissions during remediation of 903 Pad Area and B- and C-Series Ponds.</p>	<p>Prior Site activities may have caused low-level contamination. Implement control measures to mitigate potential future emissions during closure activities on A-Series Ponds and IA D&amp;D.</p>
Wind Suspension Deposition	<p>Potential long-term source for transport to surface soils and waters from low level Pu and Am surface soil and exposed sediment contamination. Plant residues with surface contamination of Pu and Am may be transported by wind. U contamination is mostly in subsurface soils, not subject to wind transport except during remediation. Plant residues containing U may be transported by wind.</p>	
Raindrop Splash Deposits on Plants (Rps)	<p>Particulates on plant surfaces due to raindrop splash are potential ongoing source of Pu and Am for resuspension by wind.</p>	<p>Little vegetation within the IA for this to be an ongoing source.</p>

V. Fauna and Flora		
Raindrop Splash (Rps)	Plant residues with surface contamination of Pu and Am may be transported by water	Significance not quantified, minor pathway
Bioturbation (Rbp)	<u>Primarily within the top 6 inches and limited to 2-3 feet</u>	<u>May be significant of redistribution process for actinide-contaminated surface soils</u>
Biopedal (Rbp)	Small amounts of contaminated soil may be transported on pelis and hooves of animals	
Vegetation Root Uptake/Recycling (Rpr)	Plant uptake of Pu and Am has been shown to be insignificant	<u>U is taken up by some plants</u>
	Surface deposition by rain-splash is much more important	A biobarrier may be evaluated for portions of the IA

Note The underlined text indicates the processes that may account for significant actinide transport within each drainage

**Figure 3 - Schematic Diagram of the Conceptual Model for Plutonium and Americium Migration at the Rocky Flats Environmental Technology Site**



**Notes**

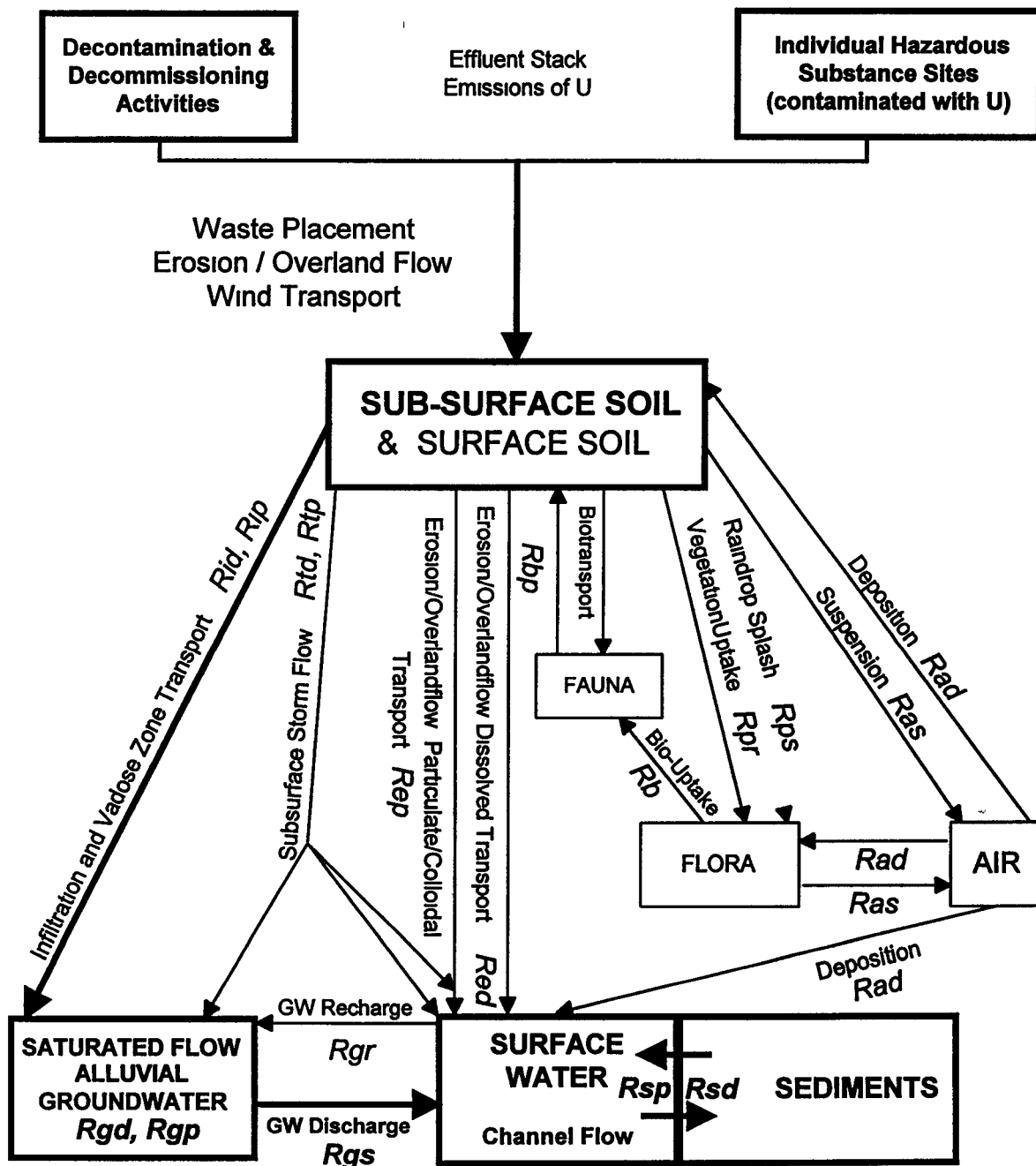
1) Boldness indicates relative importance of pathways/processes for actinide migration

2)  $R$  = Rate of actinide transport (subscripts indicate transport pathways in Figure 2)

**LEGEND**

- ◀ Not a Viable Pathway
- ← Minor Potential Pathway
- ➡ Major Potential Pathway

**Figure 4 - Schematic Diagram of Conceptual Model for Uranium Migration at the Rocky Flats Environmental Technology Site**



**Notes**

1) Boldness indicates relative importance of pathways/processes for actinide migration

2) R = Rate of actinide transport (subscripts indicate transport pathways in Figure 2)

**LEGEND**

- ◀ Not a Viable Pathway
- ← Minor Potential Pathway
- ➡ Major Potential Pathway

The Site receives an annual average of 14.5 inches of precipitation, with about 50% in the form of rain (DOE, 1995). Precipitation facilitates actinide transport. Precipitation provides the energy of raindrop impact to loosen soil particles from the soil surface. Melting snow runs off more slowly than rain. Rain and snow together provide a means for potential transport of actinide-contaminated soil across the Site landscape by overland flow and erosion mechanisms (EG&G, 1993c and RMRS, 1998a,b).

The erosion processes that occur due to precipitation and snowmelt are central to the conceptual model. Runoff from impervious IA surfaces occurs rapidly, but Buffer Zone runoff occurs chiefly on roads, steep hillslopes, and areas where culverts feed IA runoff to the Buffer Zone. Although much of the overland flow in the Buffer Zone originates from this impervious surface drainage, precipitation events greater than about 0.5 inches per 24 hours do produce runoff (EG&G, 1993a and 1993b). The runoff carries particulates, colloids, and small amounts of dissolved constituents down-slope to areas of deposition and to stream channels where channeled flow transports materials to quiescent catchments—such as the A-, B-, and C-Series Ponds— or downstream and potentially off-site.

Vegetative soil cover and soil characteristics, such as hydraulic conductivity (rate of infiltration), particle size, and the degree and stability of soil aggregation into secondary particles control the susceptibility of a soil to erosion. Dense vegetation in many areas of the Walnut Creek and Woman Creek watersheds provides protection against erosion. Small areas with less cover are interspersed throughout the watersheds. These areas and unpaved roads may account for most of the soil erosion that occurs at the Site. Hydraulic conductivity and rainfall simulation studies at the Site have found infiltration to be rapid (DOE, 1995b, Fedors and Warner, 1993, Ryan et al., 1998, and Litaor et al., 1996a and 1998). Recent AMS research on the particle size distribution of water-stable aggregates in soils from the Walnut Creek and Woman Creek watersheds has shown the Site's soils to be stable with the majority of the soils comprised of water-stable aggregates greater than 200 microns ( $\mu\text{m}$ ) in diameter (RMRS, 1998c). All of the above suggests that erosion rates for Site soils are low. However, small amounts of actinide-contaminated sediments reaching the Site surface water channels may have a significant impact on water quality with respect to the RFCA requirements.

A loading analysis of the on-site watershed channels has been produced by the AMS using historical surface water quality data (RMRS, 1998b). The analysis gives empirical estimates of the amounts of runoff, soil, and actinides reaching the surface water channels. Results indicate erosion rates may vary from negligible to about 0.2 cm per year depending on location. The loading analysis will be used to calibrate the Watershed Erosion Prediction Project (WEPP) model to present site conditions. The WEPP watershed model is being used to estimate the rates of soil erosion and sediment transport.

### **3.1.2 Channel Flow (Rsp)**

Channeled surface-water flow can transport actinides associated with particulate, colloidal, or in the dissolved phases. Resuspension of contaminated sediments in the stream channels or in the detention ponds can be caused by a variety of agents. Batch releases from the holding ponds and storms can cause turbulent flows capable of resuspending and transporting streambed sediments off-site. Wind can resuspend pond bottom sediments via wave action. Seasonal inversions of pond waters due to temperature differentials have also

been documented in Site holding ponds, which temporarily increase concentrations of several water quality constituents (EG&G, 1993d and DOE, 1996a) Fish, reptiles, waterfowl, and aquatic mammals also can cause particulate resuspension

Factors that effect actinide mobility in surface water include

- In-stream vegetation, such as cattails, that can filter the contaminated particulates,
- Diversion dams or other physical barriers that slow surface flow and enhance particle settling,
- Ice cover on ponds that prevents resuspension of pond bottom sediments via wave action,
- Oxygenation of pond waters due to wind and influent runoff, that favors insoluble metal oxide formation,
- Hydraulic efficiency of the stream channels (e g slope, pool to riffle ratio, meandering, etc ), and
- Chemical changes in wetland or deep water environments (e g pH and redox conditions)

It is important to note that actinide transport occurs through combinations of these processes and not by any single mechanism The dominant transport pathways and processes drive data needs for modeling The transport of sediments is being modeled by the AMS using the WEPP watershed model The AMS is also currently investigating relationships among actinide activity-concentrations, total suspended solids, particle size (including colloids), and dissolved species in Site drainage channels

### 3.1.3 Dissolution From Sediments (Rsd)

Sediments in the A-, B-, and C-Series ponds are contaminated with actinides Research on sediments from the ponds has shown that, in the normal environmental pH range, Pu and Am are highly insoluble and remain associated with the solid phase (Johnson et al , 1974 and Cleveland et al , 1976) Cleveland (1976) found that Pu- and Am- contaminated pond sediments extracted with pond water at pH values of 7 and 8 released from 0.00084% to 0.0015% of the Pu and 0.0011% to 0.0028% of the Am present in the sediments Current AMS investigations on the solubility and associations of Pu and Am with soils and sediments will provide further information on rates of release to surface water

U is more soluble in natural waters than Pu or Am U sorption experiments on soils, completed by Colorado School of Mines in 1997 (Honeyman, 1997), indicate that from 0.5% to 3.2% of the added U remained in solution in the aqueous phase Samples with higher clay content had less U remaining in solution These estimates are an upper-bound estimate of potential U release from sediments because it is based on sorption rather than release of contamination, and contact between the particles and the water are much greater in the laboratory than at the bottom of a pond Morphological differences between soils and sediments may also influence release

## 3.2 Groundwater Transport Pathway

After precipitation has infiltrated into the soil, it becomes groundwater The soil horizons and upper portions of aquifers, which have some pore spaces that contain water and some pores that contain air are called the unsaturated or vadose zone Water movement in the vadose zone is known as unsaturated flow The location of the vadose zone may change seasonally or after periods of high precipitation, as a result of fluctuations in the water table

(the upper surface of the saturated zone) Saturated flow occurs where all pore spaces are occupied by water (Freeze and Cherry, 1979) Discharge of groundwater to surface water is by saturated flow Actinides transported by infiltrating water into the vadose zone via macropores may be available for transport by way of either unsaturated or saturated flow (Litaor, 1996b) Each of these mechanisms will be discussed below

It has been demonstrated that groundwater is a minor Pu and Am transport pathway at the Site compared to surface water and air (RMRS, 1997 and Harnish et al, 1996, and RMRS, 1996 and 1998) However, in order to develop a complete conceptual model for groundwater transport processes the susceptibility of actinides to transport under exceptional environmental conditions is being investigated by AMS researchers Groundwater transport of U is believed to be a significant pathway and thus additional geochemical analyses are being conducted

### **3.2.1 Infiltration (Ri)**

The groundwater transport pathway of the conceptual model starts with the infiltration of rainfall or snowmelt into the soil and, with sufficient precipitation, percolation through the vadose zone towards the saturated zone (water table) This generally occurs by unsaturated flow, unless conditions are unusually wet The rate at which the infiltration and percolation occurs is related to the precipitation rate and the hydraulic conductivity of the soil The hydraulic conductivity of the near-surface soil depends on many soil characteristics, including

- The mineral and organic composition of the soil,
- Particle-size, bulk density, and porosity of the soil,
- Vegetative soil cover,
- The slope and aspect of the soil,
- The length and frequency of freeze and thaw cycles,
- Soil cracking from drying, and
- Macropores from worms, plants, small animals, and other causes

The infiltrating water carries dissolved elements in solution and soil particles and colloids, which may contain actinides, down through the soil, mainly via tiny vertical channels such as worm holes, plant root channels, drying cracks, freeze-thaw cracks, and other macropores (DOE, 1995a and Litaor et al, 1996a and 1998) The movement of soil particles and colloids with infiltrating water is called eluviation Litaor et al (1996a and 1998) collected infiltrating water at the Site from natural precipitation, snow melt, and simulated rainfall in zero tension samplers distributed at various depths down to 70 centimeters (cm) They found that a large majority of the activity did not move with the infiltrating water From 0.02% to 0.07% of the Pu and Am in the surface soil was mobilized, with 83% to 97% of this associated with particulates greater than 0.45  $\mu\text{m}$  in diameter

An increase in the flux of the infiltrating water by several orders of magnitude at the deeper sampling levels (40-70 cm) did not increase the flux of Pu or Am, indicating that these actinides were immobilized by the soil matrix as the water percolated through it These results are consistent with depth distributions of actinides measured for the Operable Unit No. 2 RCRA Facility Investigation/Remedial Investigation (RFI/RI) (DOE, 1995b), which showed that approximately 90% of the Pu and Am in contaminated soil near the 903 Pad was in the top 12 cm of soil more than 20 years after release

### **3.2.2 Vadose Zone Transport (Unsaturated Flow) (Rid, Rip)**

A perched water table occurs when a less permeable layer of material lies beneath a more permeable one, thereby perching the percolated water on top of the textural discontinuity, with unsaturated conditions existing both above and below. Perched water tables may act as storage areas for translocated actinides (Freeze and Cherry, 1979).

### **3.2.3 Subsurface Storm flow (Rtd and Rtp)**

Subsurface storm flow can be described as a dynamic, saturated shallow water table. Subsurface storm flow is rapid, saturated, near-surface lateral flow from hillslopes that can discharge to seeps and streams because the groundwater is moving rapidly at a shallow depth (Dunne, 1990, Domenico and Schwartz, 1990 and Freeze and Cherry, 1979). This subsurface flow, also known as through flow or interflow (Kirkby and Chorley, 1967 and Domenico and Schwartz, 1990), occurs where the water table is near the surface or infiltration is retarded due to shallow bedrock or soil textural discontinuities, such as a textural B soil horizon (alluvial clay horizon), in the vadose zone.

Many areas on the Site have a lower soil horizon in which the clay content increases significantly. These layers have lower hydraulic conductivity than the overlying soil and inhibit the downward flow of water. Subsurface storm flow is a potentially important pathway for actinide transport in localized surface soil contamination areas where shallow or perched groundwater discharge to seeps or stream channels.

The mobility of actinides in groundwater is dependent on whether the actinides are transported in the dissolved or particulate phase. Therefore, the phase speciation of actinides under varying geochemical conditions (reduction/oxidation [redox] potential, pH, temperature, etc.) is of particular interest to the AMS investigations. Geochemical conditions change over time in response to changing environmental factors.

It has been hypothesized that subsurface storm flow may be a significant transport process during extraordinary precipitation events (e.g., Spring, 1995) in which the soil is saturated for significant amounts of time (RMRS, 1995 and Litaor et al., 1996a). For example, the oxidation/reduction hypothesis proposes that extremely wet periods (e.g., 10- to 100-year precipitation events) may cause saturation of vadose zone soils and low redox potential. These conditions might change the phase speciation of the actinides and increase the actinide mobility from the solid soil phase (RMRS, 1995 and Litaor et al., unpublished report, 1996b). This potential transport mechanism hypothesis is under investigation by AMS researchers (Honeyman and Santschi, 1997 and 1998).

### **3.2.4 Saturated Groundwater Flow (Rgd and Rgp)**

The saturated groundwater at RFETS has been categorized into two hydrostratigraphic units based on groundwater geochemistry, core logging, and hydraulic conductivity measurements (EG&G, 1995c). The upper hydrostratigraphic unit (UHSU) consists of the unconfined saturated groundwater flow zone, in which unconsolidated and consolidated groundwater-bearing strata are in hydraulic communication. The UHSU is comprised of several lithostratigraphic units, including quaternary alluvium, colluvium, valley-fill alluvium, weathered bedrock of the Arapahoe and Laramie formations, and all sandstones within the Arapahoe and Laramie formations that are in hydrologic contact with overlying

unconsolidated surficial deposits or the ground surface. The UHSU is considered to be equivalent to the uppermost aquifer at the RFETS. The lower hydrostratigraphic unit (LHSU) is comprised of the unweathered bedrock of the Arapahoe and Laramie formations. The base of the weathered bedrock has been used as the boundary between the UHSU and the LHSU. A detailed discussion of hydrostratigraphic units is included in the Hydrogeologic Characterization Report (EG&G, 1995c).

The saturated groundwater flow is largely controlled by the topography of the bedrock. The alluvial groundwater flow is primarily lateral due to the low permeability of the underlying claystone bedrock. Preferential vertical groundwater flow and contaminant transport does not appear to represent a viable pathway for actinide migration based on an assessment of available data (Kaiser-Hill, LLC and RMRS, 1998).

### **3.2.5 Groundwater Recharge and Discharge (Rgr and Rgs)**

Actinides transported by alluvial groundwater (UHSU), in either the dissolved or particulate form, have the potential to discharge to stream channels or seeps for continued transport in surface water (groundwater discharge). Groundwater recharge occurs from the infiltration of precipitation from stream, ditch, or pond seepage.

Berzins (1994) studied the Woman Creek watershed using small flumes to quantify the interaction of the alluvial groundwater with Woman Creek. He found that the interaction of the alluvial groundwater system with the stream was seasonally dynamic. Berzins concluded that upstream reaches of Woman Creek were generally gaining flow (groundwater discharge) while downstream reaches were normally losing flow (groundwater recharge). The AMS will incorporate these findings into the conceptual model.

### **3.3 Air Transport Pathway (Ras and Rad)**

Wind erosion and transport of contaminated soils is a complex process involving resuspension, lateral aeolian transport, and saltation processes. Dead vegetation rain-splashed with contaminated soils can break down into pieces and particles that may be moved down wind. Exposed contaminated soils disturbed by bioturbation and precipitation are susceptible to resuspension and aeolian transport. Topography, wind speed and direction, vegetative and hard surface (e.g. rock or pavement) cover, soil particle size, and other parameters will be important to modeling the aeolian transport of contaminated soil. The Site AMS includes an airborne transport modeling investigation to be initiated in FY99.

### **3.4 Fauna and Flora Transport (Rb and Rbp)**

Fauna and Flora transport includes (1) raindrop splash deposition, (2) vegetation uptake, (3) and biotransport, when an animal ingests or otherwise takes in (e.g. breathing dust particles) the actinide-contaminated soil or externally carries the contaminated soil on its pelt. These mechanisms are discussed below.

#### **3.4.1 Raindrop Splash Deposition and Vegetation Uptake (Rps and Rpr)**

Raindrop impact can move soil particles from the ground surface to the surfaces of foliage, both living and dead (Whicker, 1979 and Webb et al., 1993). Precipitation provides the energy of raindrop impact to loosen contaminated soil particles from the soil. Physical

attachment of contaminated soil particles to the vegetation by raindrop splash is more likely more prevalent than on biochemical incorporation of the materials into the plant cells. Actinides have large atomic masses and small charge to mass ratio, which generally prevents the uptake of high concentrations of actinides into the cell walls of plants, although uptake is species-dependent.

Work by Whicker (1979) and Jarvis (1991) indicate that 90% or more of the Pu and Am associated with vegetation is due to soil particles deposited on the outer surfaces. The particles deposited on the vegetation are then available for transport by other processes. This includes the transport of contaminated plant material by overland flow to surface water drainage's. The significance of this pathway has not been quantified. However, Webb (1992) found that Pu associated with vegetation declined between 1974 and 1989. Unlike Pu and Am, there appears to be considerable variation in plant intake of soil U depending on the plant species (Mortvedt, 1994 and Ibrahim and Whicker, 1988).

### **3.4.2 Biotransport (Rb and Rbp)**

Biotransport occurs when an animal ingests (biouptake) or otherwise takes in (e.g. breathing dust particles) the actinide-contaminated soil or externally carries the contaminated soil on its pelt (biopedal). Animals transport the actinides with them when they migrate to other areas, both on the Site and off-site (Whicker, 1979). Bioturbation is the process whereby soil is loosened as the animals or humans travel over or burrow into contaminated soil. Such disturbances cause mixing of surface soils with subsurface soils. The result may be the movement of surface contamination to greater depths or to the surface if contamination has migrated deeper into the soil profile. Other effects of bioturbation are to increase the hydraulic conductivity over small areas, causing greater susceptibility to erosion due to removal of vegetation and loosening of the soil (Hakonson, 1998, Litaor et al., 1996a and Gonzales et al., 1995).

## **4.0 POTENTIAL OFF-SITE IMPACTS**

For the purposes of the AMS investigations, the off-site impacts pertain to potential accumulation of actinides in off-site streams, reservoirs, soils, and groundwater as well as transport of actinides through these media. The impacts implied in the conceptual model do not address human or ecological health risks, but pertain to the extent to which off-site areas could potentially receive quantities of actinides in various environmental media due to actinide transport past the current Site boundaries.

Potential migration pathways off-site, shown in Figures 3 and 4, include surface water, air, and groundwater transport. Groundwater transport is not considered a significant pathway since contaminated groundwater discharges to surface water prior to leaving the Site. Current watershed modeling by the AMS will be estimating the movement of actinides associated with sediments in stream channels as a result of soil erosion. The project will be estimating the amounts and probability of actinides moving down stream under various potential scenarios.

## **5.0 SUMMARY AND CONCLUSIONS**

The development of a conceptual model for actinide transport at the Site is an iterative process whereby the available data are compiled and integrated to develop an understanding of the Site (RMRS, 1997). The purpose of the conceptual model is to develop a mechanism for estimating rates of transport of actinides in environmental media at the Site. Data deficiencies or areas of uncertainty that become apparent as the conceptual model is developed will lead to collection of additional data and integration of the new data into the model. Major processes and data needs are shown in Attachment A.

The Site Conceptual Model for Actinide Transport is diagrammed schematically in Figures 3 and 4. Rates of transport for the significant pathways will be determined by the use of appropriate models and data developed by the AMS. Major potential migration pathways for Pu and Am are considered to be the transport of contaminated surface soil by erosion processes and the subsequent transport of the resulting sediments by surface water in the Walnut Creek and Woman Creek watersheds (Figure 1). Several minor potential pathways are also under study, including the air, groundwater, and sub-surface storm flow pathways. Transport of the colloidal and dissolved phases of Pu, Am, and U by surface water is also being investigated. Work is currently underway to estimate rate constants for these migration pathways through literature searches, laboratory experiments, and modeling.

For major migration pathways, quantification of the transport rates may include a literature search and computer modeling. A list of potential models is provided in the AMS DQO document (RMRS, 1998a). Future versions of this Conceptual Model will present quantification of the transport rates and their relationship to potential final RFETS configurations, long-term protectiveness of surface water, and downstream impacts.

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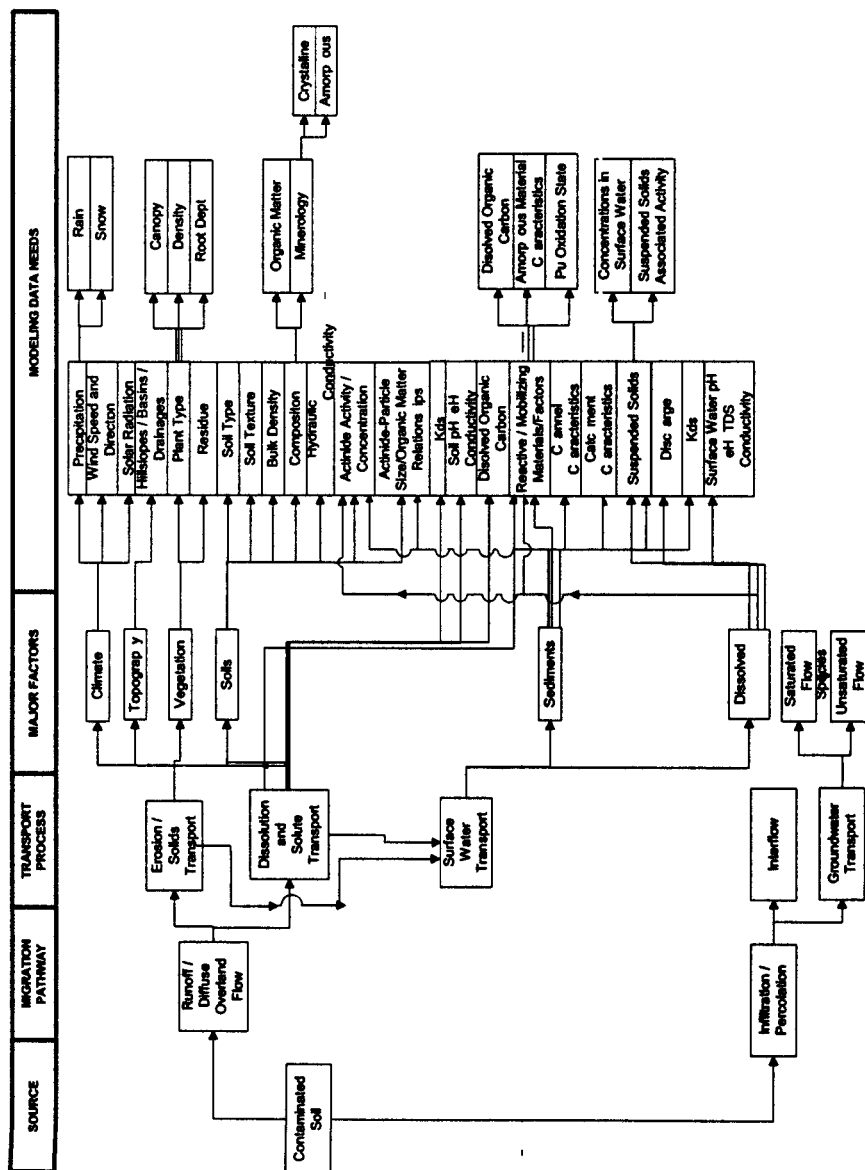
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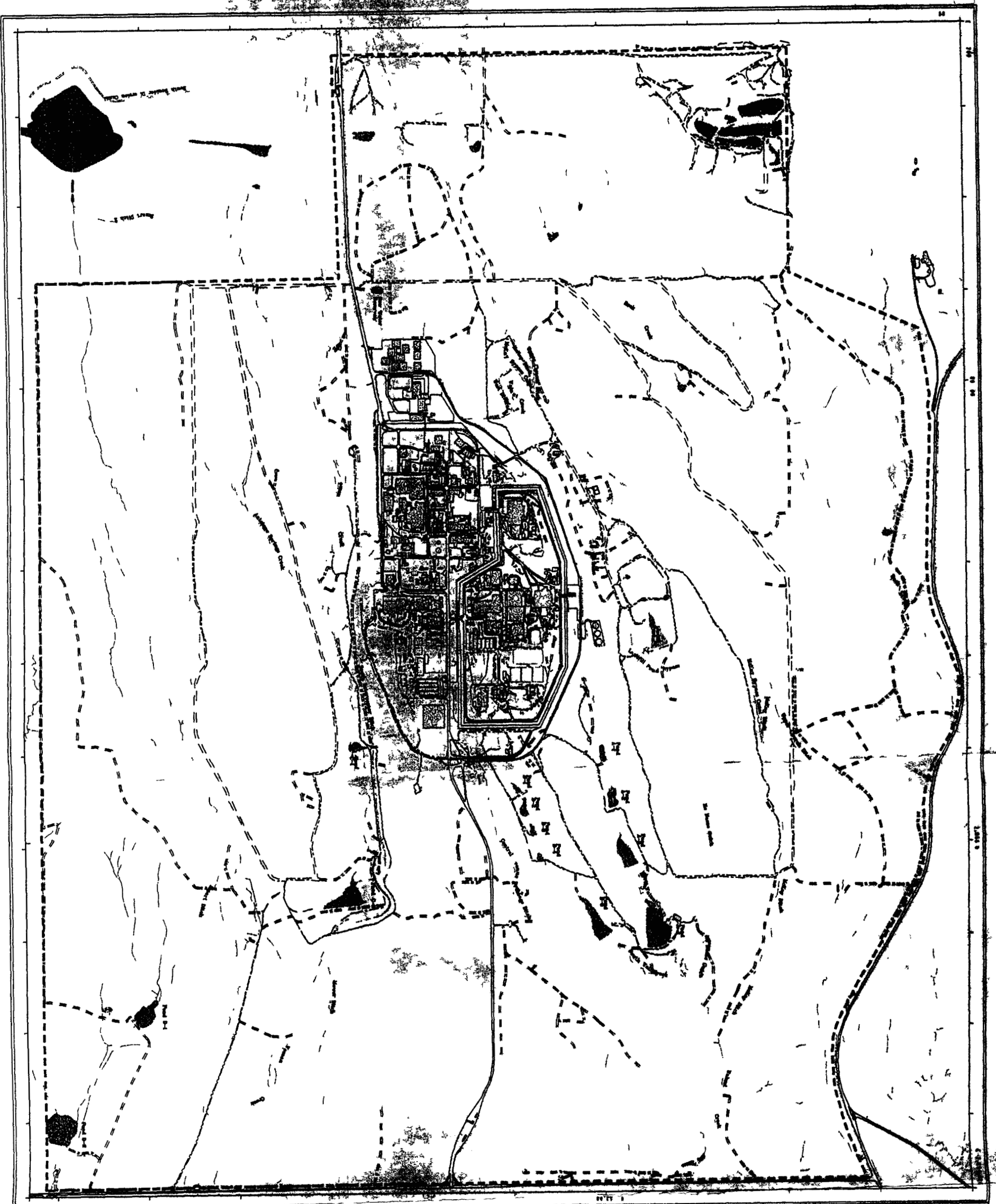
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## **ATTACHMENT A**

### **Actinide Migration Studies Major Process Matrix for Rocky Flats Environmental Technology Site Watersheds**



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**Figure 1**  
**ROCKY FLATS**  
**Drainage Features**

**EXPLANATION**

**Standard Map Features**

▀ Lakes and ponds

▬ Stream, ditch, or other drainage feature

▬ Fence

▬ Rocky Flats boundary

▬ Paved roads

▬ Dirt roads

Rocky Flats Environmental Technology Site  
Site Map  
Scale: 1 inch = 1778 feet  
Datum: NAD27  
Projection: UTM  
Zone: 18N  
Datum: NAD27  
Projection: UTM  
Zone: 18N



Scale = 1 21330  
1 inch represents approximately 1778 feet

0 1000 2000  
feet

Site: Pine Creek & Projectio  
Colorado Cent. & Zone  
Datum: NAD27

**U S Department of Energy**  
**Rocky Flats Environmental Technology Site**



Rocky Mountain  
Remediation Services, L.L.C.  
Remediation Services Division  
10000 E. 1st Avenue, Suite 100  
Denver, CO 80231

MAP ID: 98-0087

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